The Mathematics Doctorate: A Time for Change?

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The Carnegie Foundation commissioned a collection of essays as part of the Carnegie Initiative on the Doctorate (CID). Essays and essayists represent six disciplines that are part of the CID: chemistry, education, English, history, mathematics, and neuroscience. Intended to engender conversation about the conceptual foundation of doctoral education, the essays are a starting point and not the last word in disciplinary discussions. Those faculty members, students, and administrators who work in the discipline are the primary among multiple audiences for each of these essays.

Comments on the essays and on the CID are welcome and may be sent to `cid@carnegiefoundation.org`. Further information may be found at the website `http://www.carnegiefoundation.org/cid` and in the article "The Carnegie Initiative on the Doctorate", by Allyn Jackson, *Notices*, May 2003, pages 566–8.

The other Carnegie essay about mathematics, by Hyman Bass, appeared in the August 2003 issue of the *Notices,* pages 767–76.

—Allyn Jackson

One can argue, with ample evidence, that in U.S. universities the system of producing mathematics doctorates is doing very well and needs no major overhaul. It is widely recognized that however poor our K–12 mathematics education—and perhaps also our undergraduate mathematics education—might be, our graduate programs in mathematics are the best and the envy of the world. Top students from around the world are still beating on our doors to get into our doctoral programs. We train them well, and many of these students become international leaders in their research fields. Take, for example, the two 2002 Fields Medalists and the Nevalinna Prize winner. Even though the press (at least the press in Beijing, where I read the news) referred to them as French, Russian, and Indian, two received their doctoral training at U.S. universities. We also seem to be succeeding in getting new support from the federal government for mathematical sciences. The recent increase in funding for the NSF [National Science Foundation] specifically targets the Division of Mathematical Sciences, and doctoral training, in particular for U.S. students, is a core part of this new funding program. Even Hollywood seems to be working in our favor, in view of the generally positive image of mathematics generated by movies such as *A Beautiful Mind*.

However, there are many signs that not all is well with our doctoral programs. Top, talented students, especially those born in the U.S., are choosing fields other than mathematics for graduate study. Many mathematics departments, especially those outside the "top tier", are having trouble filling their graduate programs with reasonably prepared and talented students. As a field of science, mathematics is underfunded compared to other sciences. Most of our doctoral students are supported by teaching assistantships rather than by fellowships or research assistantships. Our doctoral students are taking too long to get their degrees, and they are not sufficiently and broadly trained for career paths outside of academia. Other scientists and academic administrators perceive us as an insular and, worse, irrelevant community.

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None of these symptoms are new. Most are well documented in a series of nationally commissioned reports on the status and health of our community, from the 1984 and 1990 David Reports *Renewing United States Mathematics*, to the 1998 Odom Report *The Senior Assessment Panel of the International Assessment of the U.S. Mathematical Sciences* and the 1999 American Mathematical Society report *Towards Excellence: Leading a Doctoral Mathematics Department in the 21st Century*. Indeed, over the last two decades the mathematics community, perhaps more than that of any other science, has produced many national self-studies that urge fundamental changes to our doctoral programs.

Judging from the persistence and recurrence of some of the same main issues in these reports over a period of twenty years, one can only arrive at the conclusion that very little real change has been made. And recent attempts at change have been met with controversy (e.g., the NSF's Vertical Integration of Research and Education in the Mathematical Sciences, VIGRE program; see recent articles in the November 2002 issue of the *Notices* and the May 24, 2002, issue of *Science*). Viewed against this background, the current Carnegie Initiative on the Doctorate comes at a critical juncture for our community.

Does U.S. doctoral education in mathematics need rethinking at this moment? There is no shortage of ideas about *what* we need to change. We have to decide *whether or not* we want to change.

The Goals of and Context for Doctoral Education in Mathematics

In order to understand the need for change in the mathematics doctorate, we need to consider the goals of and context for doctoral education in the discipline. What are the overarching goals of U.S. doctoral education in mathematics? How does the context of the American university affect these goals? What perspective does each of the key stakeholders bring to doctoral education?

The U.S. doctorate system has its origins in the universities of Europe, especially those of Germany. In this context our system is relatively new, and yet it has acquired certain distinguishing characteristics. One particular characteristic is how we fund our doctoral students. Most are supported by a mix of teaching assistantships (most mathematics departments are responsible for a large amount of service teaching on university campuses), federal research support (through grants to advisors and departments), and fellowships (through the federal government, private foundations, and universities). Thus, in addition to the faculty and the doctoral students, the federal government and the universities play important roles in shaping doctoral programs, because each party brings particular goals and needs to the system.

Within the profession of mathematics, among the faculty the goal and purpose of doctoral education in the field is quite clear. To borrow from the principles of the current Carnegie Initiative on the Doctorate, the goal is "generation, conservation, and transformation" of the knowledge of the discipline. To quote Lee S. Shulman, president of the Carnegie Foundation for the Advancement of Teaching, "The Ph.D. recipient is expected to serve as a steward of her discipline or profession: dedicated to the integrity of its work in the generation, critique, transformation, transmission and use of its knowledge." I very much agree with this statement. Certainly the future health of the discipline cannot be guaranteed if we cannot generate its human resources and train its next generation of leaders.

Yet we have to keep in mind that the federal government, the universities, and the doctoral students have different perspectives on the goals of doctoral education in mathematics. From the perspective of the federal government, funding for doctoral students is justified primarily by societal needs: at one time, national defense during the cold war, and now, a scientifically well-trained work force for supporting industry and the government in order to ensure a robust economy and international leadership in science and technology. The federal government is interested in the work force issue, not the specific research output generated by doctoral students.

For their part, universities support mathematics primarily for its role in providing service teaching to a large number of students from other disciplines. They pay for teaching assistantships and want qualified students—with content knowledge and communication and teaching skills—to staff them.

For the doctoral students, the purpose of the doctorate is usually more than the stewardship of an academic discipline. They care about their future careers and hence the job prospects of the discipline. Those who enter our doctoral programs expect career preparation as well as the skills and content knowledge of the discipline necessary to become a scholar and researcher.

These goals and perspectives, although quite different, need not be conflicting. And to be realistic, U.S. doctoral programs must take all of them into account.

Ensuring Our Source of Quality Doctoral Students

A key issue in any discussion on the doctorate in mathematics is our "pipeline". How do we increase the number of students in the field, and how do we ensure that we attract the best-qualified students to join the field?

Much of the problem is our own fault. Traditionally, we have expected that undergraduate students choose to enter a doctoral program in mathematics purely out of intellectual interest in the subject. Perhaps the student has been "good in math" from elementary school into college classes. Perhaps she was inspired by a teacher in an upper-division class. Our basic assumption has been if you are good at it, then surely you will want to do it. However, if the data in the many national reports are correct, that U.S. students have a declining interest in entering doctoral programs in mathematics, then our assumptions are not well founded.

Perhaps this decline is not felt as much in the handful of top mathematics departments in the country, as they continue to attract the "cream" on the top of the student pool, even as the size of the pool shrinks. But many departments, including my own (which by all measures is among the top research departments: eleventh in the 1995 NRC ranking and tenth in the most recent *U.S. News and World Report* survey), acutely feel the decline. And some suggest that we might briefly see a silver lining over the dark clouds of the recent dot-com collapse, which has led to increased applications to and enrollments in doctoral programs in all of the physical sciences. The good news notwithstanding, what this says to me is that clearly the talent pool is there, but career choice is a critical factor for potential students.

Entering a doctoral program in mathematics is usually one of many choices for a talented undergraduate student. The virtue we often preach about, the versatility of an undergraduate degree in mathematics, is true: students qualified to enter mathematics doctoral programs have many choices: mathematics, other scientific disciplines, and industries that require a good mathematics background. Some of these choices are as intellectually interesting or financially rewarding (or both) as mathematics, and many students choose other fields for a postbaccalaureate degree. Are we missing an opportunity?

One opportunity occurs as undergraduates choose majors. We should try to increase those numbers. Mathematics would seem to have an advantage over other fields, as most undergraduates are required to take at least one course in mathematics and many take more. But many freshmen and sophomores have told me something like this: "I was really interested in math in high school, but after the calculus sequence I lost my interest and chose another major." I have told students that mathematics is not just calculus and that there is a whole new world waiting for them to explore. Nonetheless, we lose many potential majors and potential doctoral students. I have often wondered if mathematics departments could offer an undergraduate "Math 101" course to give students a panoramic view of the field. Perhaps this course could be offered at the sophomore level in order to present the scope and the excitement of the field to potential majors. (I proposed such a course when I was department chair but was advised by the faculty that it would never work because it would not be a required course for any other majors.)

As I mentioned above, besides pure intellectual reasons, career prospects are a critical factor in a student's decision. In my opinion, mathematics faculty members could do a much better job of presenting employment prospects for those with undergraduate and graduate degrees. For example, the career paths most obvious to undergraduate math majors are high school teacher and perhaps actuary, respectable professions certainly but not commonly viewed as the center of excitement in either science or the business world. Similarly, students often assume that with a doctorate in mathematics their career choices will be limited. The career path most obvious to them is becoming a professor, preferably one in a department that values and allows time for research. However, in reality only a small percentage will become faculty members in a research-oriented department; simple arithmetic will confirm this, given the small number of research universities in relation to teaching-focused colleges and universities and the mode of nonexpansion in most universities. The number of new Ph.D.'s produced each year far exceeds the number of current research faculty who retire. Available data (see the article "2001 Annual Survey of the Mathematical Sciences (Second Report)" in the August 2002 issue of the *Notices*) show that only about 25 percent of mathematics Ph.D.'s are finding jobs in doctoral-granting academic departments; most others who find jobs in academia are at colleges with heavy teaching duties. The doctoral degree often takes six to seven years, and the opportunity cost, as well as lost potential earnings, constitutes a high barrier for entry. Moreover, the *apparent* noncentral role of mathematics in the frontiers of science and technology and the necessary specialization inherent in a doctoral program would seem to limit employment options outside of academia. Against this background and considering the other career choices which do profitably leverage good mathematics undergraduate training, it is not surprising to find that only a small percentage of our math majors choose to pursue a doctorate in mathematics.

The above is the case with U.S. students. Many of our doctoral programs have a high percentage of foreign students who are often the most talented students in their countries of origin. When these students enter our doctoral programs, they are focused on mathematics as a career. However, as time passes they begin to appreciate the array of career choices available to them. Some choose to switch to other fields with better prospects, such as computer science and finance. This can be quite frustrating for the mathematics departments that gave them the initial financial support.

My point is that to ensure a good source of quality students for our doctoral programs, we have to consider the potential candidates' perspective and address their concerns. We have to make the doctorate itself as attractive as, or more attractive than, other fields. The doctorate must take less time to complete than it takes currently. We must recognize the fact that most of our "products" will not become professors in research universities, and so we must train them in a way that better prepares them for a broad range of career options.

To ensure a steady talent pool for the doctorate, mathematics departments should start by improving the undergraduate math major, making it more attractive and providing research opportunities to students well before they graduate. Departments should also get more involved with K–12 mathematics curricula and teacher training programs. The whole "pipeline" need not feed into the doctorate; in fact, it is beneficial to have students branching off to other math-related careers. But if we do not pay attention to increasing the source of good students, then we risk turning our doctorate into a kind of esoteric priesthood for the few.

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Ensuring That Mathematics Is Part of Science

Another critical issue is the role of mathematics in the overall science enterprise. Despite good formal relationships with other science communities, often for political expedience in arguing for increased funding for science in general, mathematics generally has not been seen by other scientists to be at the frontiers of science. This may come as a surprise to some in our community: historically, mathematics has always been at the core of science as both its language and its method of analysis. Giants of the past such as Newton, Gauss, and Poincaré are all great mathematicians with enormous impact on other sciences. But how often do we see articles on mathematics in *Science* or *Nature* these days? And even in the few articles that do appear, the mathematics is usually not immediately relevant to the other sciences. Many scientists I have talked to view mathematicians as bright people who "prove theorems" but who are not relevant to the frontiers of their particular field of science. The notable exception is perhaps theoretical physics: historically, its interaction with mathematics has been extremely beneficial for both. But even the most heralded of the recent interactions (such as string theory) have quite a few skeptics in physics. In any case, the influence of deep mathematics is felt at only a portion of the frontier of modern physics.

Why should mathematics concern itself with being at the frontiers of science? One can argue that mathematics can do quite well on its own. History has shown that many purely internally driven developments in mathematics have ultimately proven to be essential for science. However, I see at least two reasons for getting our community more directly involved in science and working at its frontiers. One is lost opportunities; the other is our doctorate.

Let us consider the first: lost opportunities. Many problems at the frontiers of science are fundamentally mathematical in nature. By being inward-looking and not getting involved, mathematicians are missing out on the chance to make a real impact on science. Take two recent examples I have come across. The 2002 Nobel Prize in Chemistry was given for work that involved a mathematical framework for determining the 3D geometry of large biomolecules by using NMR [nuclear magnetic resonance] techniques. Similarly, a recent issue of *Science* (January 24, 2003) included an article on a breakthrough by two chemists: a fast mathematical algorithm for doing NMR analysis that is based on Fourier analysis. These contributions are mathematical and are of immediate relevance to science, yet our community has not been involved.

Science is not only fertile ground for the application of mathematics, it can also give inspiration for mathematics itself in the form of new problems and new ideas. The opportunities for interaction with science are plentiful and well documented. See, for example, the 1999 NSF report *Mathematics and Science* by Wright and Chorin, and the 2000 NSF report *Opportunities for the Mathematical Sciences*. Others in our community have also called for a closer integration of mathematics within science (see the article "Mathematics and sciences" by Weinan E in the *Beijing Intelligencer*, August 2002).

Working to place mathematics at the frontiers of science can also be beneficial to our doctoral programs. If we make mathematics more explicitly central to the science enterprise, our doctorate will be more attractive to students who are intellectually interested in the interaction between math and other sciences. It will also provide a means to broaden the perspective of our doctoral students. If backed up by appropriate changes in doctoral training, our students will be more versatile and more attractive in the job market.

I would even go as far as advocating that we require some formal interaction with at least one other science during doctoral training. This is probably common practice for "applied" mathematics students, but it should not be limited to them. This interaction could take several forms: a course or a seminar series in another department, a joint research project with someone from another discipline, in-depth reading on the scientific background of a mathematical problem.

Our doctoral students should be encouraged to explore all areas of science, especially the current frontiers. They should not limit themselves only to the "classical" areas, such as classical theoretical physics. New opportunities for mathematicians are present in many exciting new frontiers in nanoscience, biomedical research, the Internet, and computational science, to name just a few examples.

Ensuring Societal Support for Mathematics Doctoral Education

Finally, mathematics must consider the issue of support for doctoral-level education in the discipline. Few would argue that the health of mathematics doctoral programs, at least in their current forms, depends critically on governmental support. Unlike the other sciences, we can, in theory, carry on most research and train graduate students without federal support. But this would make mathematics much less attractive to potential students than other fields. To ensure continued governmental support, we need to convince society at large that mathematics is worth supporting. We must ensure that outsiders, from other scientists to the public at large, understand the purpose of our field without needing a detailed understanding of its inner workings. It is certainly not intrinsically obvious to the public that research in mathematics at the doctoral level is worth supporting any more than the humanities or the arts. Society expects a return on its investment. Government support for academic research has always been tied to short-term national needs and benefits to society. My experience from serving on NSF advisory committees suggests that societal support for science is based on three kinds of expected returns: (1) long-term investment (fundamental research and human knowledge), (2) impact on the economy and furthering national goals (e.g., national defense), (3) education and development of human resources. The history of U.S. governmental support for science bears this out. Vannevar Bush proposed our current system of national support for academic scientific research after the Second World War to prepare the nation for national defense. Sputnik led to further strengthening of support for science as a response to the Soviet challenge. Will September 11, 2001, be the new Sputnik? The current rationale for structuring support at the NSF is "Ideas, People and Tools": the "people" are as important as the "ideas".

What does this mean for the mathematics doctorate? The first two returns described above call for a balance between fundamental (including curiosity-driven) and targeted research, even though some of us would prefer more of the former. The third return emphasizes the importance of ensuring a stable pipeline of talented students, trained in a broad way to meet a variety of societal needs. Most of our recent success in garnering more funding from Congress for the mathematical sciences is, in fact, based on our discipline's promise to deliver a combination of all three returns. It is certainly not an act of benevolence from Congress to correct past "injustice" in funding levels. Our promise requires the mathematics community to pay more than lip service to the important role of mathematics in society, the economy, and the private sector, and to the impact of mathematics on other disciplines. Our promise should be reflected in how we train our students, including our graduate students. After all, if our products do not satisfy societal needs, then society will stop supporting us and will hire students from other disciplines.

Ensuring That Mathematics Doctoral Education Meets Its Goals

After laying out the different perspectives and goals of the stakeholders in mathematics doctoral education, pointing out the obvious importance of ensuring a stable and talented pipeline of doctoral students by making our doctorate more attractive and more relevant to a variety of career choices, and arguing for a stronger integration of mathematics in science in our doctoral programs, I hope I have provided a context to begin a discussion on concrete steps that we can take to improve on our doctorate.

Actually, if we can agree on the context and the goals, then the steps are quite natural. In fact, the plethora of reports published by national organizations (a useful and comprehensive list is provided in Appendix C of *Strengthening the Linkages between the Sciences and the Mathematical Sciences,* published by the National Academy of Sciences in 2000, based on the work of a committee chaired by

Thomas Budinger) contains a wealth of specific ideas and suggestions.

I cannot add many new ideas to the many that have been suggested, but I can offer four practical steps in light of the goals and perspectives of the stakeholders in mathematics doctoral education and the critical issues of the discipline. I hope these steps and accompanying examples will prompt discussions within individual departments so that they arrive at their own plans, based on local strengths and constraints, for improving their doctoral programs:

1. We should make doctoral education in mathematics more attractive to students and competitive with other fields.

• Expose students to the full range of mathematics. We should emphasize the intellectual challenges as well as usefulness and applications of mathematics.

• Shorten the time to degree. For example, departments could streamline qualifying examinations without lowering academic standards. We could offer summer courses to better prepare the students for their examinations. We could also bring students into research groups as early as possible rather than after several years spent preparing for these examinations.

• Ensure ample research support for doctoral students. At present, many doctoral students are supported by nonresearch-related jobs, such as TAs and tutoring, which take time away from their research and increase time to degree. Faculty should explore all sources of funding and consider various strategies for supporting students. It might be better, for example, to have a smaller doctoral program and provide better funding for the students.

2. We should prepare our doctoral students for a broad range of future careers.

• Expand students' awareness of rewarding career possibilities in mathematics. We could take a big step in this direction by changing departmental culture so that nonacademic careers are as respectable as academic careers. One step in this direction would be to invite a wide variety of outside speakers to talk with the students: a department could invite, for example, former graduates who have successful careers both inside and outside academia, leaders from the mathematics community who can provide a national perspective and a broad science perspective, and potential employers.

• Make teaching an integral part of doctoral training. Many of the graduates who do go into academic settings will have jobs with heavy emphasis on teaching. We could, for example, offer formal TA training courses, assign senior TAs to mentor junior ones (with faculty supervision), select a few TAs to be in charge of a small number of classes, and offer teaching awards to recognize the best TAs and motivate the others.

• Broaden the training of doctoral students. Students should learn about different subfields within mathematics and interact with disciplines outside mathematics. Students should be encouraged to keep abreast of the latest developments, not just in their own research area, but also in mathematics as a whole and in science in general. We should require this broad understanding of the field—and of science—of all students, not just those in applied mathematics.

• Develop professional skills. We must make sure our students leave our programs with essential professional skills. For example, we could provide training in mathematical writing and presentations, proposal writing, and mentoring of junior graduate students and undergraduates.

3. We should improve mentoring during the doctoral training.

• Mentor for the student's career. Early in the mentoring relationship, doctoral mentors must have their students' careers in mind. We should recognize that we train both the researcher and the scholar.

• Help students develop independent research approaches. We should encourage our students to learn the history and the broader literature of a research problem. We can encourage students to formulate their own problems rather than to solve the next problem in the mentor's research program. We can assign broadly defined research areas that have a potential for postdoctoral investigations rather than niche areas that are potential dead ends.

• Help students find the right mentor. Departments should have a formal mechanism for exposing the full portfolio of faculty research programs to doctoral students early on. For example, faculty could give lectures on their research programs; these lectures would be intended for doctoral students looking for thesis advisors. Faculty could offer research area seminars and encourage new students to join. We should encourage our students to attend department colloquia; we should invite good expository speakers and ask them to use part of their lectures to reach out to graduate students.

• Encourage students to mentor each other. We should encourage graduate students to form their own organizations and have senior students mentor junior ones. The senior students can also be involved in organizing the faculty research lectures.

• Improve career counseling. We could formalize career counseling and introduce it early in a doctoral student's career. We should encourage students to attend national and regional conferences and workshops (and, to the extent possible, provide funding for them to attend).

4. We should adopt some effective practices from other sciences.

• Work in groups. Working in groups is a prevalent feature of almost all areas of science and engineering research. The benefits are peer support and a gentler introduction to a research area.

• Include beginning students in research groups. This should be done before they advance to candidacy to reinforce the idea that the main emphasis of a doctoral education is the research experience, not courses and examinations.

• Drop the barriers between "pure" and "applied". Most sciences are not organized according to a "pure" versus "applied" dichotomy. Each sub-discipline within a department usually has faculty with interests ranging from foundational to applied. For example, chemistry departments are not organized into "pure chemistry" and "applied chemistry" units. In physical chemistry, one of the common subfields, one often finds theoreticians who solve Schrödinger's equations, experimentalists who look for new molecules and their properties, computational chemists who do numerical simulations, and material chemists who design new materials. Doctoral students in chemistry are thus in a better position than are their mathematics counterparts to be aware of the whole range of problems in their subfield beyond their own research problems. Is there something worth emulating here?

Conclusion

In the final analysis, perhaps the most critical questions facing doctoral education in mathematics are not those about how to improve it. The critical questions are these: Do we have the will to make serious improvement, and is now the time to do so? Specific ideas such as those I offer above have been pointed out for more than two decades, yet until very recently very few of them have been widely adopted. What is different now? What suggests that change is possible now?

For one, money speaks. And it is speaking now. The NSF has been quite proactive recently in using its funding programs to effect changes in the mathematical sciences doctoral programs. The most notable is the VIGRE program, which specifically calls for an overhauling of doctoral programs. The funding varies from several hundred thousand dollars to close to a million dollars for each department, a sum most departments would consider substantial. The NSF's rationale for VIGRE is that not only is it good for the discipline, it also appeals to Congress: it is the mechanism that allowed the NSF to obtain funding for mathematical sciences from Congress. The NSF made a successful case, arguing for the importance of maintaining a pool of well-trained U.S. doctoral students in the mathematical sciences, and thus obtained extra funding for implementing the program.

As the VIGRE program currently goes through its first review after an initial three years, it has generated its share of controversy (see "VIGRE turns three" by Rick Durrett in the November 2002 issue of the *Notices*, and his "Opinion" piece in the same issue; see also "NSF moves with VIGRE to force changes in academia" in the May 24, 2002, issue of *Science*). Some leading departments, including some that have not been funded by VIGRE or recently lost the funding, are complaining that the NSF is attempting a form of social engineering of the doctorate and is thus interfering with the long traditions in many top departments. The restriction of VIGRE to U.S. students has also created problems at some departments. Of course, the matter worsened after September 11, 2001, with tightened issuance of visas to students from "sensitive" countries. Despite the controversies, however, it is generally agreed that VIGRE has had a healthy influence on the mathematics doctorate, but its full long-term effects still remain to be assessed.

But there is another reason that this might be the moment for important change in the mathematics doctorate: the explosion of exciting new opportunities in, and competition from, other areas of science and technology in which mathematics has the potential to play a big role. Many have pointed out that, several decades ago, the mathematics community relinquished the enormous opportunity offered by the advent of computer science (see Susan Landau's editorial in the March 2000 issue of the *Notices*). Are we going to repeat the blunder by letting the current revolutions in nano- and biomedical sciences pass us by?

The question of whether or not we make the improvements we need remains fundamentally a cultural issue. Our action cannot be dictated from any one source of authority. Change must be instigated by faculty. Yet faculty are often the most resistant to change: it is human nature to base decisions on one's own experience, and when some of us were graduate students, things were quite different. Real change, however, requires real leadership from individuals and institutions. The NSF, at least, is trying to effect change. But real change in mathematics doctoral education must be initiated from within our own community.

Do we have the will to make significant changes to our doctoral programs now? Do we want real changes, or do we simply want the national reports to say the right things only for the expedience of the political process of bringing in more resources to the community? I suggest we look forward and that we do so for the long-term interest of our discipline and for the next generation of doctoral students.

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